Seasonal Changes of Chlorophyll *a* Standing Stocks and Oceanographic Conditions under Fast Ice near Syowa Station, Antarctica, in 1983/84

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1983/84 昭和基地周辺定着氷下のクロロフィル *a* 現存量と環境条件の季節変化

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要旨: 昭和基地周辺定着氷下のクロロフィル *a* と水温，塩分などの海洋環境条件を測定した．1983 年 2 月から 1984 年 1 月の間，水温および塩分はそれぞれ −0.94–−2.11°C, 32.42–34.70 の範囲であった．この年の特徴として，5 月に海氷が流失し，6 月に表層から深層まで均質の水となり，7 月下旬には過冷却水が表層付近に見られた．この現象は 1982 年の状況と異なっていた．クロロフィル *a* 濃度は 1 月から 2 月の間に最大となり，3 月中旬には減少した．その濃度は 6 月から 10 月までは 0.1 mg chl. a/m^3 以下であり，12 月初旬に再び増加する傾向が見られた．1984 年 1 月中旬に測定されたクロロフィル *a* の水柱積算量は 1983 年の同じ時期の量の半分以下であった．この低い現存量は，1983 年 10 月から 1984 年 1 月にかけての積雪に起因して，水中の光量が少なかったためと推測される．

Abstract: Phytoplankton pigments and oceanographic parameters were measured in water column under the fast ice near Syowa Station (69°00′S, 39°35′E) from February 1983 to January 1984. Water temperature and practical salinity ranged from −0.94 to −2.11°C and from 32.42 to 34.70, respectively. After the flowout of sea ice in May 1983, very unusual event in recent years, the water column was mixed vertically in June, and then supercooled surface water beneath the newly formed ice appeared in late July, which differed remarkably from the phenomena in the preceding year. In this study, maximum chlorophyll *a* concentration of 4.99 mg/m^3 was recorded in middle February 1983, and it descreased in middle March. The winter minimum less than 0.1 mg chl. a/m^3 was observed from June to October, and the concentration increased again after early December. The standing stocks of chlorophyll *a* in middle January of the present year (1984) were less than half of those in the preceding year (1983). This could be explained by smaller light penetration into the underlying water between spring and summer of 1983/84 probably due to thicker snow cover on the sea ice comparing to that in 1982/83.

1. Introduction

A large number of oceanographic works in the Southern Ocean were reviewed by DEACON (1937, 1963), BRODIE (1965) and others, and some biological investigations

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were performed by EL-SAYED (1970) and HOLM-HANSEN *et al.* (1977). These studies dealt mainly with the ice-free waters. Owing to the difficulties in accessing to ice-covered waters, relatively a few works on oceanography under fast ice have been made (BUNT, 1960; LITTLEPAGE, 1965; HOSHIAI, 1969; WAKATSUCHI, 1982; FUKUCHI *et al.*, 1984, 1985a).

As part of the BIOMASS (Biological Investigations of Marine Antarctic Systems and Stocks) programs, shore-based surveys on marine ecosystems under fast ice were achived in the Japanese Antarctic Research Expedition (JARE) from 1982 to 1985 (JARE-23, -24 and -25). The present authors carried out the second year survey in JARE-24 and describe in this paper the seasonal changes of vertical distribution of chlorophyll *a* in relation to the change of oceanographic conditions. The results are compared with those reported in the preceding year (FUKUCHI *et al.*, 1984, 1985a, b) and from the northern open Antarctic Ocean.

2. Materials and Methods

Field surveys were carried out from February 1983 to January 1984 at four stations in the area around Syowa Station (69°00′S, 39°35′E). Stn. 1 was located in the Kita-no-seto Strait, Stn. 5 was in the central part of the Ongul Strait and Stn. 3 was between Stns. 1 and 5. The sampling site of Stn. 5 was substituted by Stn. 4 until April because of the inaccessibility due to bad ice condition (Fig. 1). The present stations were located in the same positions described in FUKUCHI *et al.* (1985a). The depths to the bottom at Stns. 1, 3, 4 and 5 were approximately 12, 38, 160 and more than 700 m, respectively. Seawater samples were collected using Nansen bottles with reversing thermometers from the following depths: 2, 5, 8 and 11 m at Stn. 1; 2.5, 5, 10, 15, 25 and 35 m at Stn. 3; 2.5, 10, 25, 50, 75, 100 and 150 m at Stn. 4; 2.5, 10, 25, 50, 75, 100, 150, 200, 400 and 600 m at Stn. 5. In addition to those samples, water samples for supplemental analysis of plant pigments were also collected at 5, 15 and 35 m at Stns. 4 and 5. Water temperature, practical salinity, dissolved oxygen, pH and nutrient

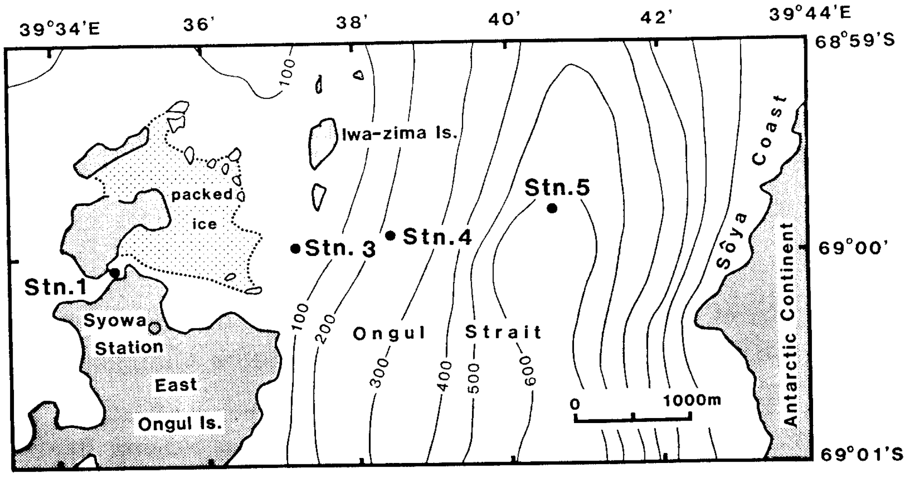

Fig. 1. Sampling sites near Syowa Station (69°00′S, 39°35′E), East Antarctica. Submarine topography is redrawn after FUJIWARA (1971).

salts were measured by the same methods described in FUKUCHI *et al.* (1985a). The concentrations of chlorophyll *a* and phaeopigments were measured with a Hitachi model 650-40 spectrofluorometer according to the procedure modified by ARUGA (1979) from the method described in STRICKLAND and PARSONS (1968).

Data on air temperature and global solar radiation are cited from the results of routine meteorological observation by JAPAN METEOROLOGICAL AGENCY (1985a, b).

3. Results

3.1. Climate and ice conditions

The ten-day mean of air temperature was slightly higher than −1.0°C in January and February 1983, and was almost lower than −15°C in July and August. During the latter period, it occasionally dropped below −20°C (Fig. 2). Seasonal variation in global solar radiation at Syowa Station was extreme; the radiation reduced to undetectable level during the period from late May till July (Fig. 2). The changes of thickness of sea ice and overlying snow at each station are shown in Fig. 3. A number of puddles were formed around each station in early February 1983, but the ice became firm again till March. The fast ice flowed off from the coast around Syowa Station and open sea appeared on 3 May 1983. This was a quite unusual event in the present area, and the observation was interrupted until the sea surface was covered by the newly formed fast ice in early June. The new ice grew rapidly from May to July and attained to the maximum thickness in August, which was maintained till late December. The puddles were formed progressively with the increasing air temperature and solar radiation in late December.

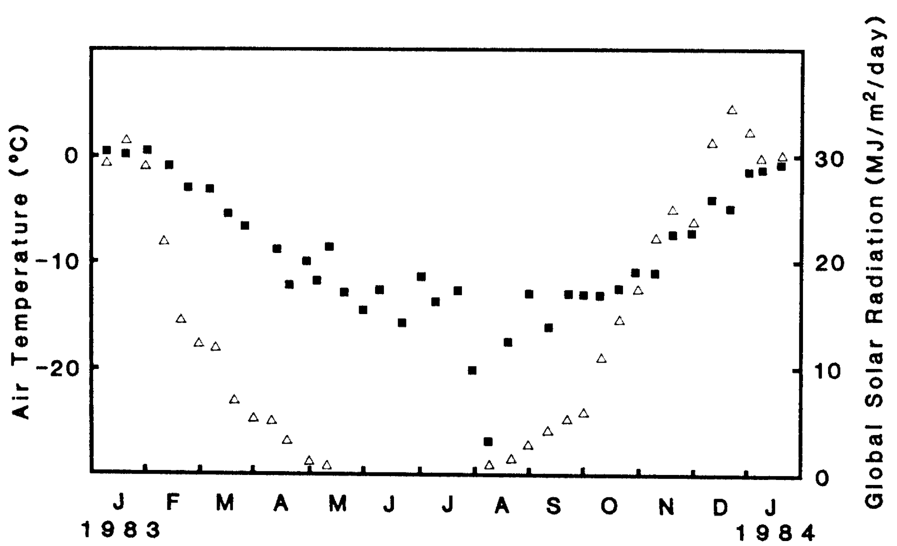

Fig. 2. Seasonal variations of global solar radiation (open triangle) and air temperature (solid square) in ten-day mean at Syowa Station recorded from January 1983 to January 1984. Data are cited from JAPAN METEOROLOGICAL AGENCY (1985a, b).

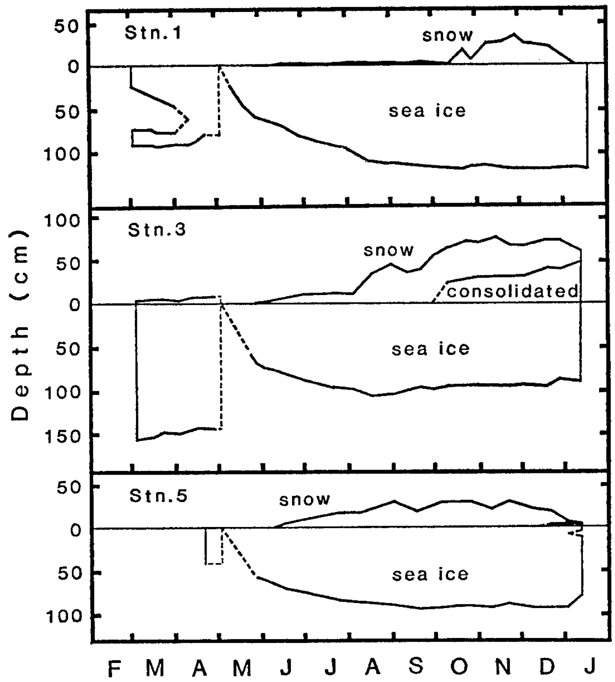

Fig. 3. Seasonal changes of the thickness of ice and overlaying snow at Stns. 1, 3 and 5.

3.2. Oceanographic conditions

Water temperature and salinity ranged from −0.94 to −2.11°C and from 32.42 to 34.70, respectively. Vertical gradient of temperature in the upper water column was the steepest in February 1983 due to formation of warm (>−1.2°C) surface water (Fig. 4). The sea water of less than 33.00 in salinity was observed in the upper layer in March and April at three stations. After the outflow of ice cover in May 1983, the water was vertically mixed and salinity as well as temperature became homogeneous (Fig. 5). The supercooled surface water appeared in late July (Fig. 4). By the last mentioned period, salinity increased to more than 34.00 and the extremely high salinity water exceeding 34.50 was formed in the upper 5 m in mid-winter. The increase of water temperature at the surface in spring 1983 was slow. This regime differed from that of 1982. In summer (middle January), salinity decreased again to less than 34.0 at the surface (Fig. 5).

Dissolved oxygen concentration in the upper layer was high from December to February. The highest value (10.79 m*l*/*l*) was observed at 2.5 m at Stn. 4 in February 1983. The concentration was more or less uniform in June–December (Fig. 6). The pH was also high in December–February and uniformly low in the rest seasons. The highest pH value of 8.33 was observed at 2 m at Stn. 1 in March 1983, whereas the lowest value of 7.90 was at 600 m at Stn. 5 in September 1983 (Fig. 7).

Nutrient concentrations were generally high throughout the year (Figs. 8–11). Although the concentration of nitrate-N temporally decreased from more than 30 μ-at/*l* to less than 10 μg-at/*l* in the upper 10 m in February 1983, the concentrations of nitrite-N, silicate-Si and phosphate-P changed little seasonally.

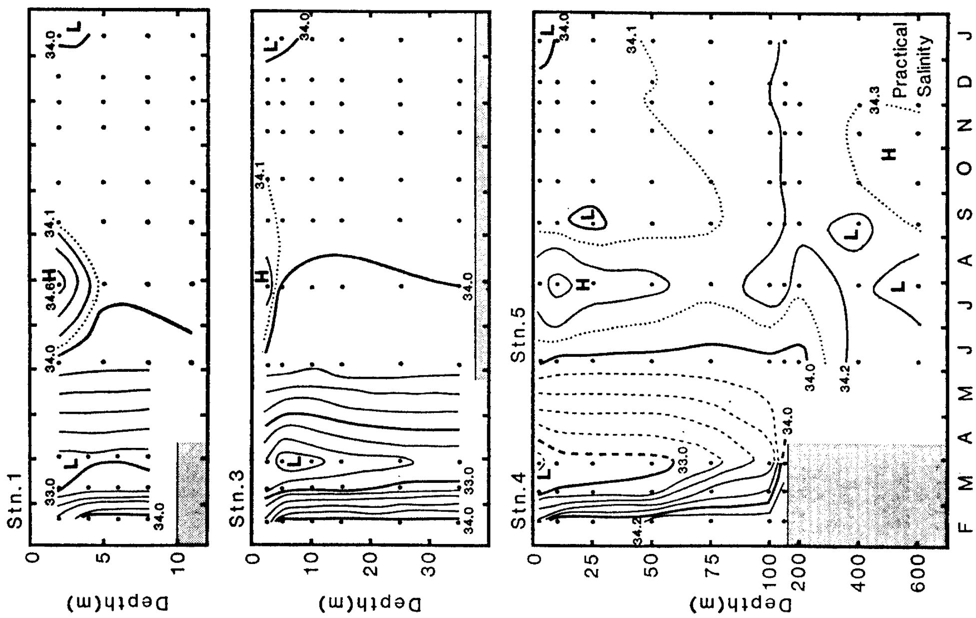

Fig. 5. Depth-time series of practical salinity at Stns. 1, 3 and 5.

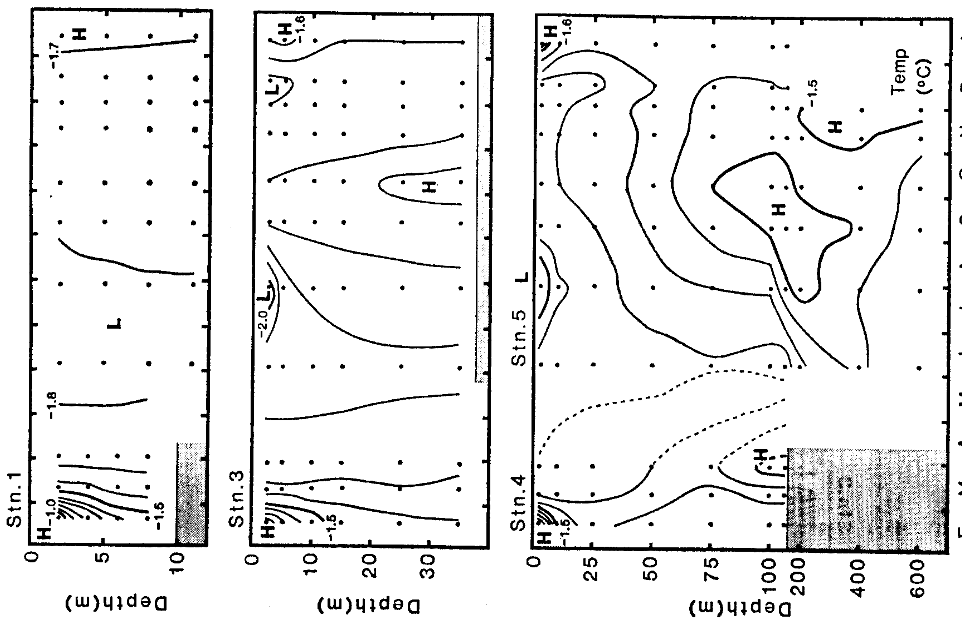

Fig. 4. Depth-time series of water temperature (°C) at Stns. 1, 3 and 5.

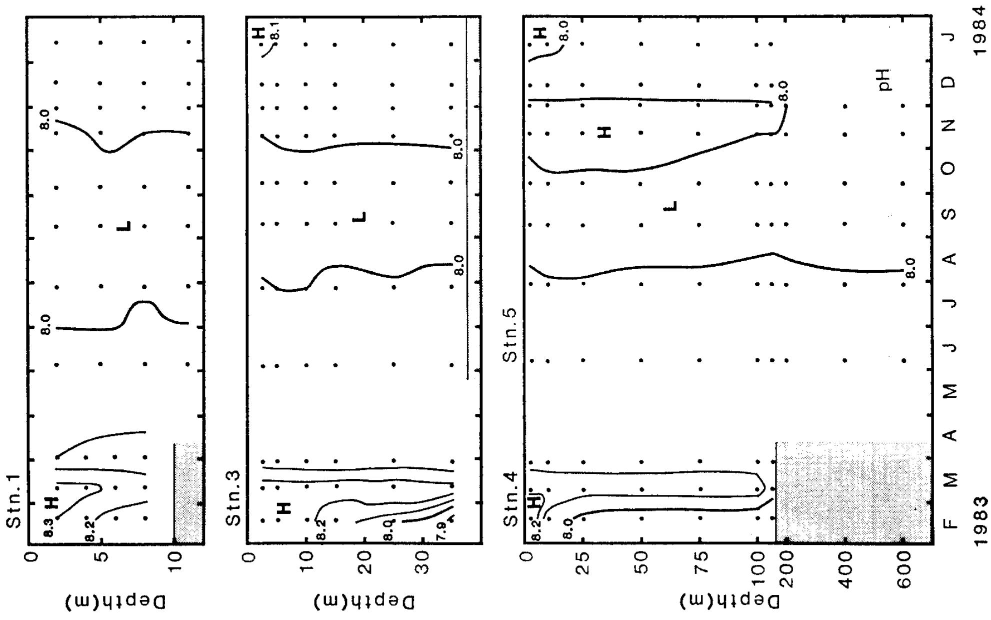

Fig. 7. Depth-time series of pH at Stns. 1, 3 and 5.

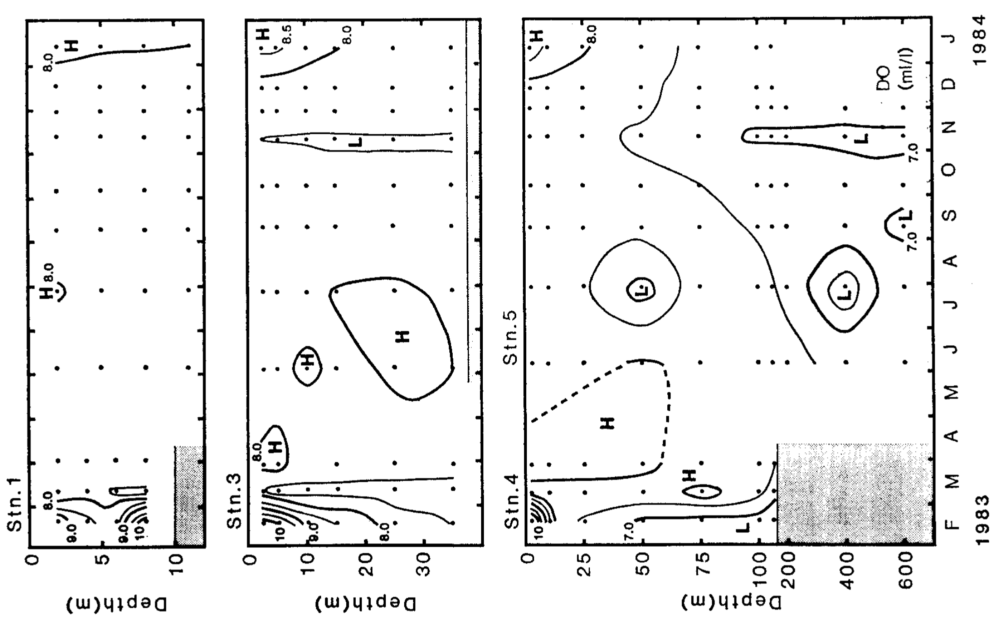

Fig. 6. Depth-time series of dissolved oxygen (ml/l) at Stns. 1, 3 and 5.

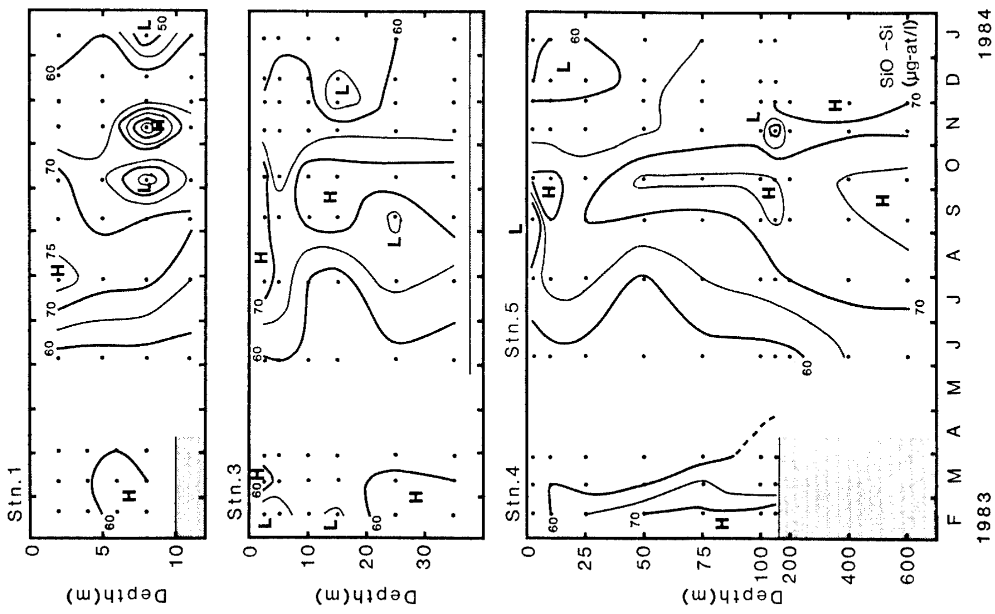

Fig. 9. Depth-time distribution of silicate-Si (μg-at/l) at Stns. 1, 3 and 5.

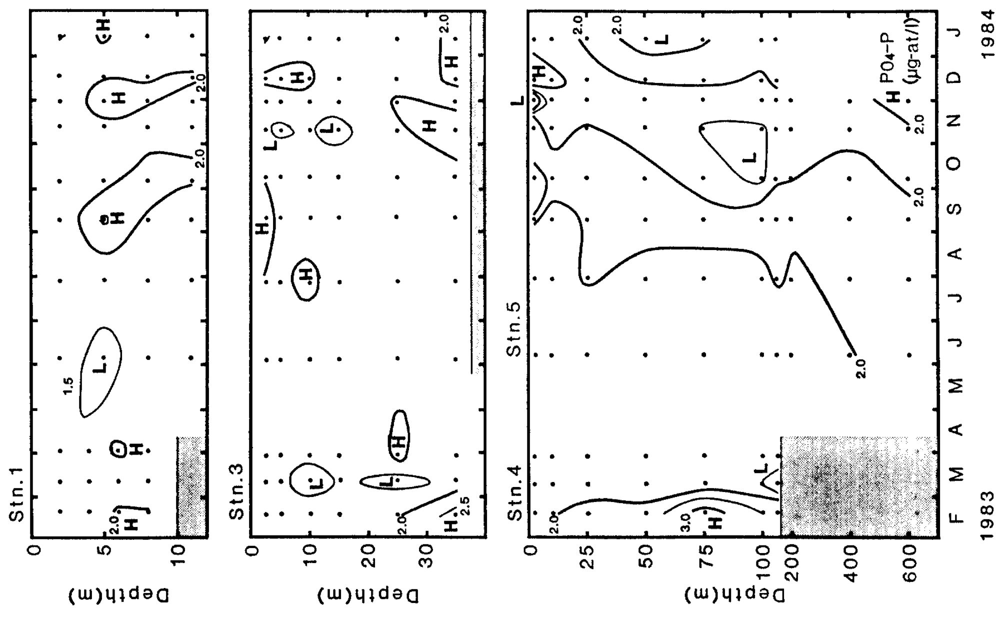

Fig. 8. Depth-time distribution of phosphate-P (μg-at/l) at Stns. 1, 3 and 5.

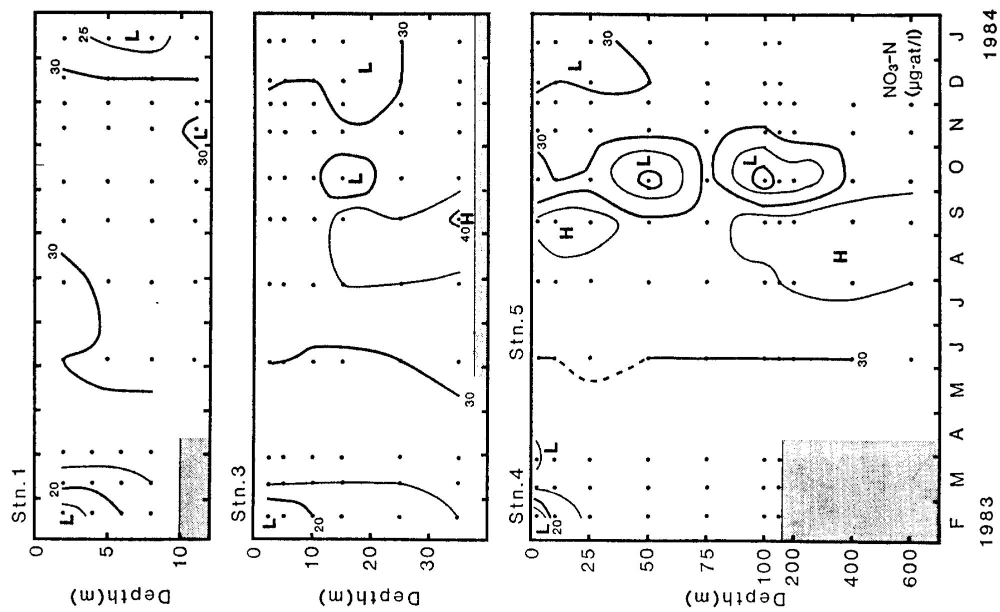

Fig. 11. Depth-time distribution of nitrate-N (µg-at/l) at Stns. 1, 3 and 5.

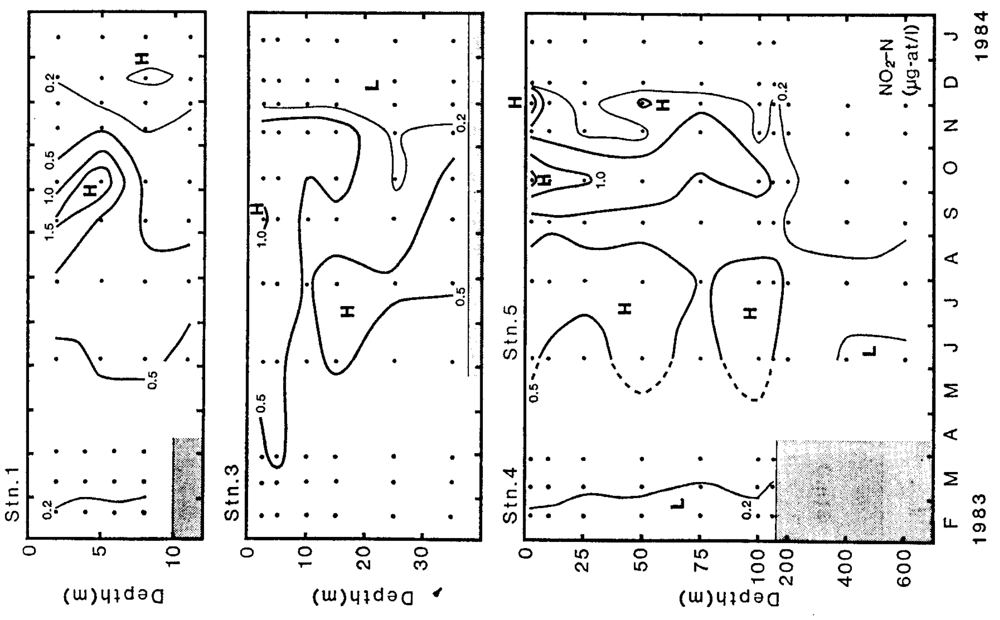

Fig. 10. Depth-time distribution of nitrite-N (µg-at/l) at Stns. 1, 3 and 5.

3.3 Chlorophyll *a* standing stock

The chlorophyll *a* concentrations were high in the upper layer in February 1983 at all stations and were more than 1.0 mg chl.*a*/m^3 in January 1984 in the upper 10 m at Stns. 3 and 5. The maximum concentration of 4.99 mg chl.*a*/m^3 during our observation was reached in February 1983, whereas the maximum value had exceeded 11 mg chl.*a*/m^3 in January 1983 (FUKUCHI *et al.*, 1984). The low concentrations less than 0.1 mg chl.*a*/m^3 were commonly observed from June to October (Fig. 12). Percentage of chlorophyll *a* to the sum of chlorophyll *a* and phaeopigments (pigment ratio) varied in the similar pattern as chlorophyll *a* (Fig. 13). The seasonal variations of integrated chlorophyll *a* standing stocks through water column at the three stations are shown in Fig. 14. The maximum value occurred between middle January and middle February. The stocks decreased remarkably in March at all stations, and reached the minimum in August at Stn. 1 and in September at Stns. 3 and 5. The gradual increase of stocks began in September at Stn. 1 and in October at other stations and its steep increase occurred in January.

4. Discussion

The salinity of less than 33.00 was observed in the upper 50 m in March and April, which was lower than that in the preceding year 1982 (>33.50, cited from FUKUCHI *et al.*, 1985a). This suggests that melting of ice during this season of the present year was extensive. After the flowout of fast ice, the vertical structure of physical and chemical parameters in the water column became homogeneous, which was also a distinctive feature in the present year. It is reasonable to speculate that the wind-generated vertical mixing might have occurred to the depth when the sea surface was exposed in early May, because the mean wind velocity for the first ten days in May was as high as 12.0 m/s (JAPAN METEOROLOGICAL AGENCY, 1985a). After freezing of the surface water, a remarkable stratification of water was established and a supercooled and saline water layer was observed just beneath the new ice in July. This water mass was probably formed by cooling with low temperature air under thin ice condition and by the resulting brine exclusion from the rapidly developing sea ice (Figs. 2 and 3).

The nutrient concentrations in the present area were higher than those in the region north of the Antarctic Convergence (DEACON, 1963). Among the nutrient salts, only nitrate-N concentration decreased in summer when chlorophyll *a* concentration increased, but enough nitrate-N (9.8 μg-at/*l*) still remained. The limiting level of nitrate-N for phytoplankton growth was reported to be 2 μg-at/*l* (EPPLEY, *et al.*, 1969). This means that no deficiency for nitrate-N occurred in the present area even at the peak of phytoplankton increase, or that the phytoplankton in this area grew under nutrient-rich conditions.

Chlorophyll *a* concentrations (mg/m^3) and integrated chlorophyll *a* standing stocks (mg/m^2) in water column throughout the year are summarized in Table 1. Chlorophyll *a* concentrations in the upper layer in February 1983 were higher than those reported from the Antarctic open waters, which ranged from 0.1 to 1.0 mg/m^3 with the mean value less than 0.5 mg/m^3 (EL-SAYED and MANDELLI, 1965; EL-SAYED, 1970; FUKUCHI, 1980; YAMAGUCHI *et al.*, 1985). By combining the present results and those in the

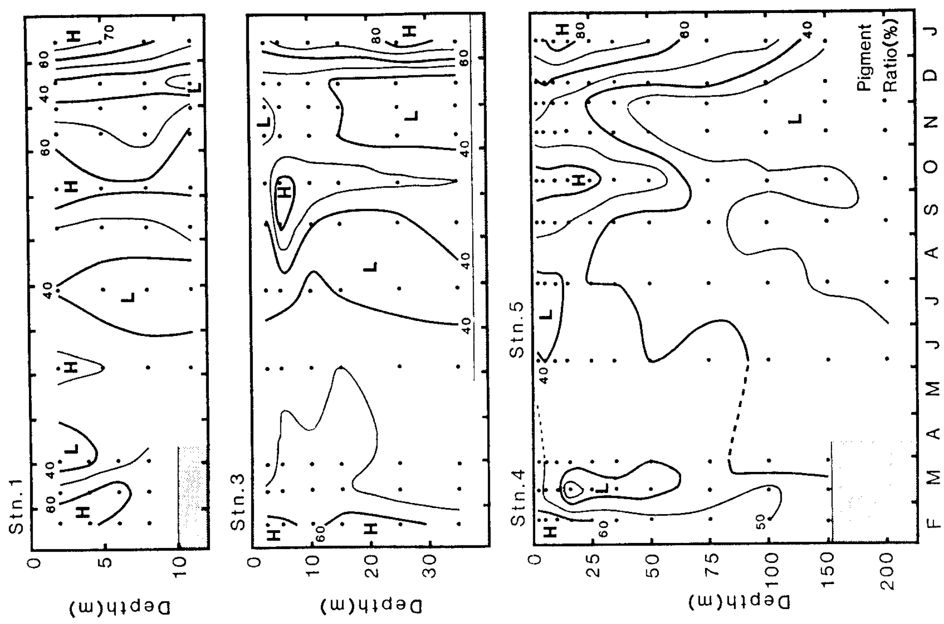

Fig. 13. Depth-time series of percentage of chlorophyll a to the sum of chlorophyll a and phaeopigments (pigment ratio, %) at Stns. 1, 3 and 5.

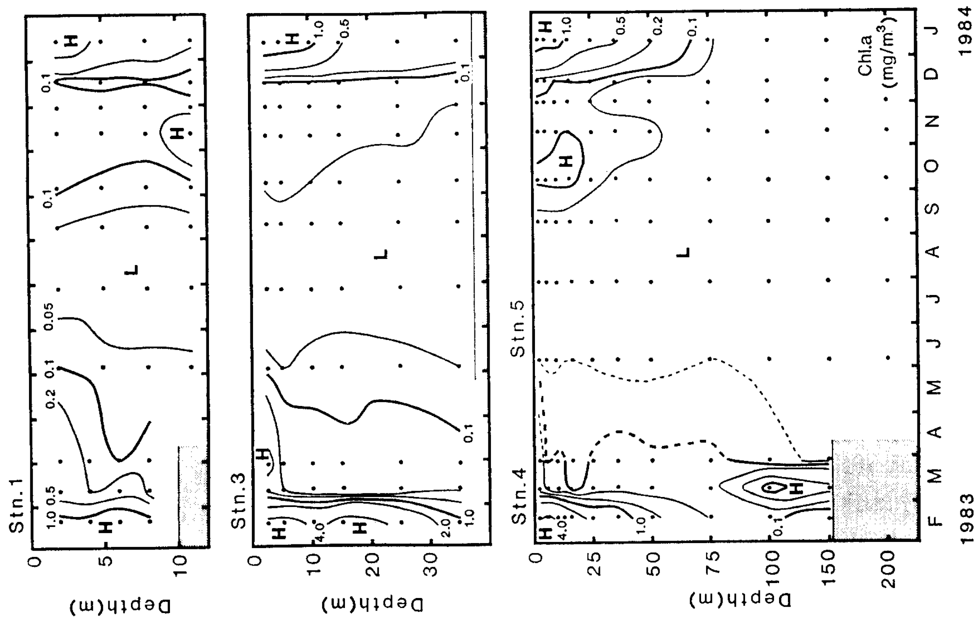

Fig. 12. Depth-time distribution of chlorophyll a (mg/m³) at Stns. 1, 3 and 5.

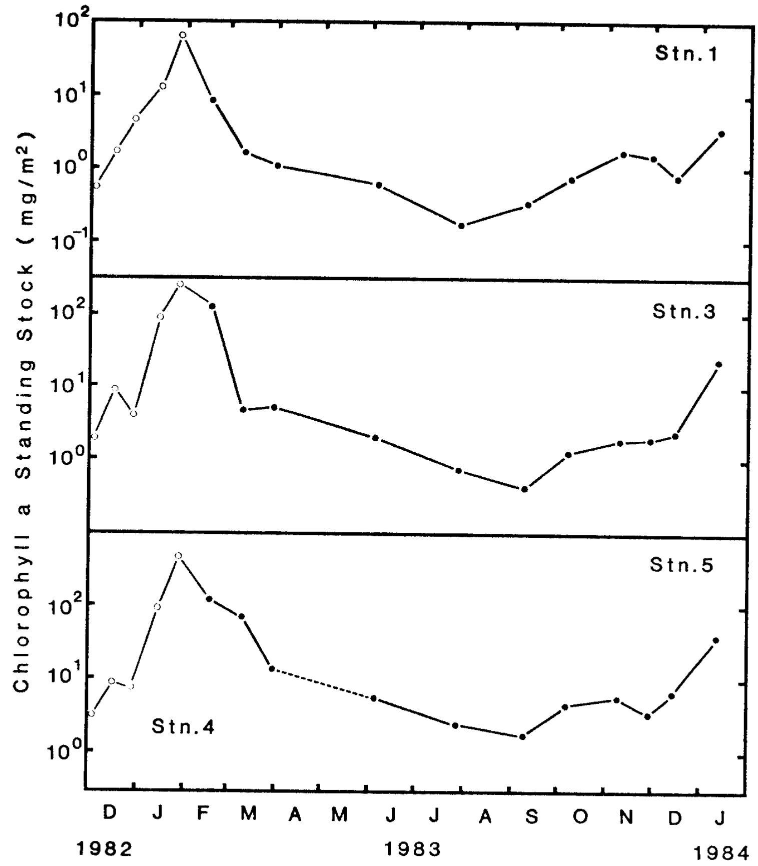

Fig. 14. Seasonal variations of integrated chlorophyll a stocks from the uppermost through the lowest layers sampled at Stns. 1 and 3, and through the upper 150 m at Stns. 4 and 5. Open circles denote the stocks which are calculated by the authors from the data cited from FUKUCHI *et al. (1985b).*

preceding year (FUKUCHI *et al.*, 1984), it is clear that one sharp peak of the summer bloom occurred in the ice-covered sea around Syowa Station between middle January and middle February (Fig. 14). HOSHIAI (1969) also demonstrated that one peak of bloom occurred between spring and autumn in the Kita-no-seto Strait in 1967. On the other hand, KREBS (1983) reported that the three blooms (spring, summer and fall blooms) occurred during the period from November 1972 to March 1973 in Arthur Harbor (64°46′S, 64°06′W) near Palmer Station. This difference might be attributable to the fact that the surface is exposed from spring to autumn in Arthur Harbor, whereas the sea near Syowa Station is almost permanently covered with fast ice.

Comparing the chlorophyll *a* stocks in middle January, those in 1984 are less than half of those in 1983 (Table 2). This difference can be attributed to the difference of light intensity and water temperature, because the nutrient salts existed enough for phytoplankton growth in this area, as mentioned above. It is well known that the solar radiation and water temperature are the major important factors governing the growth of phytoplankton in the Antarctic Ocean (EL-SAYED and MANDELLI, 1965; NEORI and HOLM-HANSEN, 1982). Our unpublished data obtained at Stn. 1 revealed that, despite the solar radiation increased 1.5 times from late October to late December

Table 1. Range of chlorophyll a concentration (mg/m^3) in the upper 11 m at Stn. 1 and in the upper 15 m at Stns. 3 and 5, and of integrated chlorophyll a stocks (mg/m^2) throughout water column obtained in the present study.

Station No.	Period of observation	Chl. *a* (mg/m^3)	Σ Chl. *a* (mg/m^2)
Stn. 1	Feb. 18, 1983–Jan. 13, 1984	0.02–1.60	0.151–8.26 (2–11 m)*
Stn. 3	Feb. 16, 1983–Jan. 12, 1984	0.01–4.99	0.716–121.1 (2.5–35 m)*
Stn. 5 (4)	Feb. 17, 1983–Jan. 11, 1984	0.02–4.75	0.980–119.2 (2.5–150 m)*

* Integrated in the range.

Table 2. Differences in the integrated chlorophyll a stocks and the increases of mean water temperature in the upper 10 m between summers of 1982/83 and 1983/84. The values in 1982/83 are cited from FUKUCHI et al. (1985b).

	Date	Stn. 1	Stn. 3	Stn. 5
Σ Chl. *a* (mg/m^2)	Jan. 14–15, 1983	12.49 (0–10 m)	85.69 (0–34 m)	90.68* (0–100 m)
	Jan. 11–13, 1984	3.58 (2–11 m)	24.78 (2.5–35 m)	40.18 (2.5–150 m)
Increase of temperature from Oct. to Jan. (°C)	1982/83	−1.81–−1.56	−1.80–−1.26	−1.84–−1.14*
	1983/84	−1.75–−1.67	−1.69–−1.61	−1.82–−1.49

* The available data at nearest position to Stn. 5 are cited.

1983, under-ice light intensity increased 3.0 times due to the decrease of overlying snow. This indicates that the light penetration into water column is largely controlled by the thickness of the overlying snow. Since the puddles developed well in the summer of 1982/83 compared with those of 1983/84, the under-ice light intensity was possibly lower in 1983/84 than in 1982/83. This might result in the difference in levels of chlorophyll *a* standing stocks in the underlying waters between two summers. On the other hand, the difference of water temperature between 1983 and 1984 observed in the present area was very small (Table 2) compared with the range tested (−1.8 to +5.0°C) by NEORI and HOLM-HANSEN (1982) in the Antarctic open waters. Hence, the contribution of water temperature might be very small. However, its influence is not well known on the growth of phytoplankton under sea ice, living in a narrowly fluctuating low temperature condition. Further investigations should be done on this point.

The thickness of snow covering the fast ice, which regulates the light penetration into the underlying water column, is the major factor controlling the phytoplankton growth in the ice-covered seas. The present results indicate that the magnitude of such a year-to-year difference in level of phytoplankton stocks could exceed factor 2 in the sea area around Syowa Station, as compared at the time of the same season.

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